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16. ABSTRACT

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JOURNAL ARTICLE

Comparison of an Optical Particle Size Monitor and a Cascade Impactor for In-Stack Source Testing

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■ Particle size measurements by a prototype in-stack optical particle size monitor are compared to concurrent particle size measurements by an in-stack cascade impactor at three coal-fired fly ash sources. The results indicate that the optical monitor and impactor size measurements defined similar particle size distributions between 0.2 and 20 μm. Particles smaller than 0.2 μm, as expected, were not observed by the optical sizer. Particles larger than 20 μm were also not expected to be detectable, but the optical instrument may have some sensitivity to the larger size particles. Mean size measurements by the optical instrument were always larger than median size measurements by the impactor. The difference was 16 and 36% for two test conditions where the fine particle fractions below 0.2 μm were small. The difference increased to 57 and 151% for two test conditions where the fine particle fractions below 0.2 μm were large.

Introduction

The most commonly used instrument for measuring the size of particles in source emissions is the in-stack cascade impactor. Cascade impactors of various design have been commercially available for many years. They have been studied extensively and their value for particle size measurement is well established. One inherent problem with these impactors, however, is that they require the extraction of a representative sample of the particles from the effluent. Extracting representative particle samples can be difficult, particularly when liquid aerosols are involved. In this case, in situ sampling is advantageous. Another inherent problem associated with impactors is the time required to obtain particle size data. The impactor is first inserted into the stack where it is heated to the temperature of the effluent. After heating, the effluent is sampled for a short time at a predetermined rate. Then the impactor is removed from the stack to cool before disassembly and removal of the size-selective samples. Later, the samples are weighed and the data plotted. This delay is undesirable when the effects of changes in plant processes and operation on particle size are being studied. For such studies, a real-time, continuous particle size analysis is desired.

This report describes tests of a new in-stack optical particle size monitor that has been designed for particle size studies in which near real-time, in situ, continuous sizing measurements are desired. Particle size data obtained with the optical size monitor are compared to size data obtained concurrently with an in-stack cascade impactor at three coal-fired fly ash sources.

Experimental Section

Optical Size Monitor. The in-stack optical size monitor was developed for the U.S. Environmental Protection Agency (EPA) by the Leeds & Northrup Co. They have described the instrument and its theory of operation in detail in reports of its development (*1–3*). Only the major features will be outlined here.

The monitor and associated dequipment are shown in Figure 1. They are all portable. The transceiver–probe assembly is the largest component and weighs 70 lb. The monitor has been designed to make five size discrimination measurements within the size range of 0.2–20-μm diameter and a volume mean diameter measurement for the same size range. It has been designed to operate on sources with particulate emission controls where the concentration range is 0.01–1.0 g/m^3. Measurement integration times between 5 s and 12 min can be selected. A complete list of operating characteristics is shown in Table I.

Table I. Operational Characteristics of Stack Particulate Monitor

size range (particle diameter)	0.2–20.0 μm
size discrimination	five volume fractions with centers at 0.3, 1.0, 3.5, 7.5, and 15 μm and a volume mean diameter between 0.2 and 20 μm
mode of operation	low-angle forward scattering and 90° polarization-dependent scattering
anticipated loading range	0.01–0.1 g of material/m^3 (0.023–0.23 grains/ft^3 or 4–40 ppb by volume with s.g. of 2.5)[a]
operational range	4–400 ppb (0.023–2.3 grains/ft^3)
measurement time	signal integration time selectable from 5 s to 12 min
duct velocity	1.5–18 m/s (5–60 ft/s)
duct temperature	260 °C maximum (500 °F)
instrument temperature	2–43 °C (35–110 °F)
power requirements	one 20-A, 115-V, 60-Hz outlet
Physical Specifications	
probe dimensions	152 cm long (60 in) by 9 cm diameter (3 1/2 in)
sample slot dimensions	2.5 × 36 cm (1 × 14 in)
transceiver–probe assembly	203 × 25 × 25 cm, 31.8 kg (80 × 10 × 10 in., 70 lb)
control console	38 × 41 × 25 cm, 9.1 kg (15 × 16 × 10 in., 0 lb)
electronics power supply	23 × 41 × 25 cm, 6.4 kg (9 × 16 × 10 in., 14 lb)
blower	74 × 48 × 43 cm, 22.7 kg (29 × 19 × 17 in., 50 lb)
probe material	type 316 stainless steel (except for optical components)

[a] s.g., specific gravity.

For the measurement, the probe is inserted into the stack effluent through a standard 4-in. sampling port. The effluent flows through a slot in the probe. A beam of light from a HeNe laser in the transceiver is directed along the center axis of the probe. In the probe–slot area, the light is scattered by the cloud of particles in the effluent as it flows through the slot. The forward-scattered light is collected at four angles between 1° and 10° by four fiber optics cables, which bring this scattered light from the end of the probe to the transceiver outside the stack where it is measured. In addition, two fiber optics cables collect perpendicular and parallel polarized light scattered at 90° by the particles. A schematic of the fiber optic light scatter collector locations is shown in Figure 2. In the transceiver, the six light-scattering intensities are measured and amplified. The amplified signals are then transmitted by cable to the control console/data processor where a microcomputer analyzes them and computes the five volume

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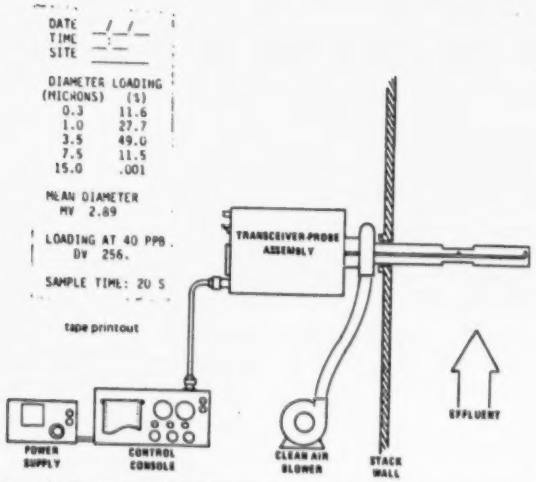

Figure 1. Optical particle size monitor with associated equipment and format of tape printout.

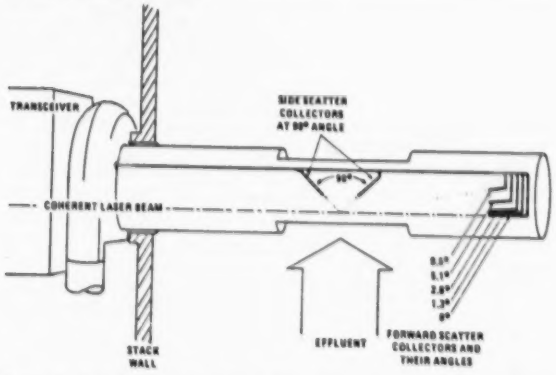

Figure 2. Locations of the fiber optic light-scatter collectors of the optical particle size monitor.

size fractions and the mean diameter of the particles in the emission between 0.2 and 20 μm. A permanent record of the measurements is printed on tape with a compact printer in the control console (Figure 1). The printout includes lines for listing date, time and site of measurements, and data on the five size fractions, the mean diameter, the particle volume concentration (loading), and sample time. The loading data are uncalibrated and not used in this study.

An outline of the light-scattering theory of the instrument is relatively simple. The angular scatter pattern of particles larger than about 1 μm becomes more forward directed as the particles increase in size. The four low-angle forward-scatter channels of the instrument measure this increased forward-scatter pattern to obtain size–concentration information on these larger particles. The angular-scatter pattern of small particles does not change with size in the forward direction, but the particles polarize light scattered at 90°. The 90° side-scatter measurements and coherent characteristic of the laser light are used to measure the degree of polarization of the side-scattered light to obtain size–concentration information on these smaller particles. For a more definitive discussion of the theory and experimental verification of this instrumental technique, see ref *1–3*. Additional information on the forward-scatter principle used by the instrument for the large particle measurements can be found in a report by Wertheimer and Wilcock (*4*).

Cascade Impactor. The in-stack impactor used for size-selective sampling of the test sources was the University of Washington Mark III cascade impactor. The Mark III impactor is a seven-stage impactor that separates the samples into eight size fractions (including backup filter). The aerodynamic particle size classification range of the impactor is approximately 0.3–25 μm in diameter for spherical particles, with a sampling rate of 1.0 ft^3/min and a particle density of 1.0 g/mL. For particles with greater density, the sizing range shifts toward smaller sizes. For irregularly shaped particles, the size-range classification represents an aerodynamic equivalent classification to spherical particles with the same densities. Additional information on the University of Washington impactor and procedures for its operation can be found in a report by Pilat et al. (*5*). The operating procedures recommended by the manufacturer were followed during this study.

Test Sources. Comparative tests of the optical and impactor particle sizers were made on coal-fired power plant emissions at three test sites. Two were field test sites at eastern coal-fired power plants, and one was a laboratory test site where coal-fired fly ash aerosol was generated into a stationary source simulator facility (SSSF).

At the first coal-fired power plant (power plant 1), the unit tested was rated at 600 MW and was burning medium (~2%) sulfur coal. Samples of the effluent were obtained from a verticle-flow duct located down stream of the plant's electrostatic precipitator (ESP) particulate emission control equipment and before the induced draft (ID) fan and stack. The duct was rectangular (9.75 m wide × 2.13 m deep) and contained a horizontal row of 13 10-cm diameter ports across the width. Two adjacent ports separated by approximately $^2/_3$ m near the center of the duct were used for inserting the samplers approximately 1 m into the effluent.

At the second coal-fired power plant (power plant 2), the unit tested was rated at 140 MW and was burning low (~1%) sulfur coal. Samples of the effluent were obtained from the stack. The 3-m diameter steel stack was located on the plant roof and contained a series of six ports oriented around its circumference and accessible from the plant roof. Two adjacent ports with relative orientation of 45° were used for the samplers. The optical measurements were made 1 m into the stack, and the impactor samples were obtained at a point approximately $^1/_2$ m to the side. The stack sampling site was located down stream of the plant's ESP particulate control equipment and ID fan.

The SSSF is a closed, rectangular-loop 56-m-long wind tunnel. The wind tunnel was designed to simulate the velocities, temperatures, humidities, and CO, CO_2, SO_2, NO, and particulate concentrations expected at stationary sources.

Particulate concentrations were obtained by continuously injecting powders into the air stream with a fluidized-bed particulate generator located approximately 8 m before the test section. After passage through the test section, the particulates were removed from the air stream as they passed through baghouse filters, which were located approximately 15 m past the test section. The test section of the tunnel was a horizontal section of duct 12 m long by 0.62 m high by 0.92 m deep with four sampling ports along the duct length. For a detailed description of the SSSF and its performance, refer to ref 6.

For these tests, the air in the SSSF was at room conditions, flowing at a velocity of approximately 13 m/s, and only fly ash was injected into the air stream. The ash was obtained from the ESP collection at the second coal-fired power plant described above. A Donaldson Company Acucut particle centrifuge was used to remove the large

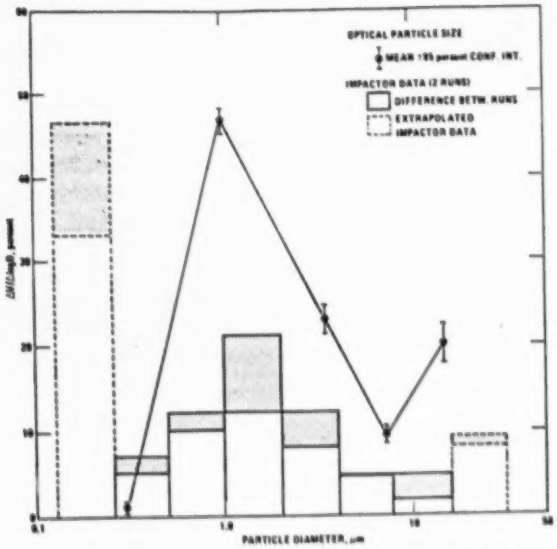

Figure 3. Optical and impactor particle size data for coal-fired power plant 1.

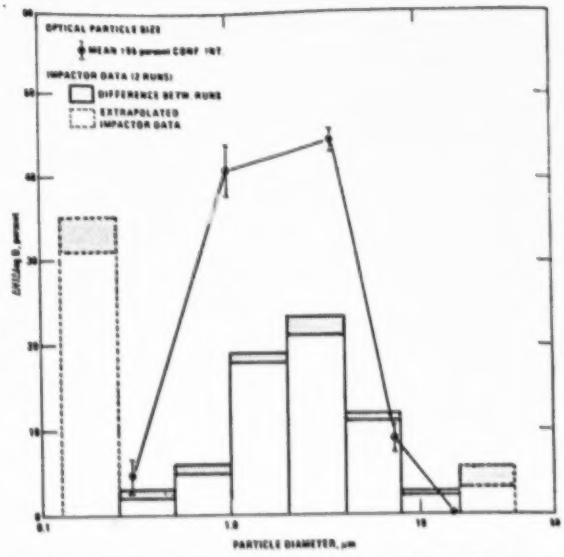

Figure 4. Optical and impactor particle size data for coal-fired power plant 2.

particles and clumps of particles from the ash. The samplers were inserted into the center of the test-section duct through adjacent ports separated by 1.7 m.

Results and Discussion

Comparisons of the two particle size measurement methods at the three sources are shown in Figures 3–6. Each figure shows bar graphs of two impactor particle sizing runs and a line graph of concurrently made optical particle sizing runs. The difference between the upper and lower values of the bars is the difference observed between the two impactor runs. At each source, additional impactor measurements (without optical measurements) showed that these bar graphs and their high–low range are representative impactor size measurements for the sources. The two end bars are shown in dashed lines to indicate that the actual lower and upper boundaries of the size distributions are not defined by the impactor. These end bars presume the upper and lower limits are 0.125 and 32 μm and are shown only for the purpose of graphically illustrating the relative amounts of very small and large particles in the sources. In reducing the impactor data, a density of 2.5 g/mL was assumed for the particles after Smith and McCain (7).

The data points shown for the optical particle size measurements are the average for 8–14 sizing runs taken during the two impactor runs. The high–low range shown for each of the data points is the 95% confidence interval range for the data. The optical sizer run times ranged from 20 s to 3 min. The impactor run times ranged from 10 to 20 min.

The data from the first coal-fired power plant are shown in Figure 3. The most obvious features of these data are that the impactor indicates a peak in the size distribution between 1 and 2 μm, a large amount of particles below 0.25 μm (~35% by volume), and a substantial amount of particles above 16 μm (~9% by volume). The optical sizer defines a particle size peak around 1 μm and a second peak around 15 μm.

When the two curves are compared, it is apparent that the optical sizer did not respond to the large amounts of very fine particles indicated by the impactor below 0.25 μm. This result was to be expected since the lower sizing range limit of the optical sizer is 0.2 μm. The optical sizer

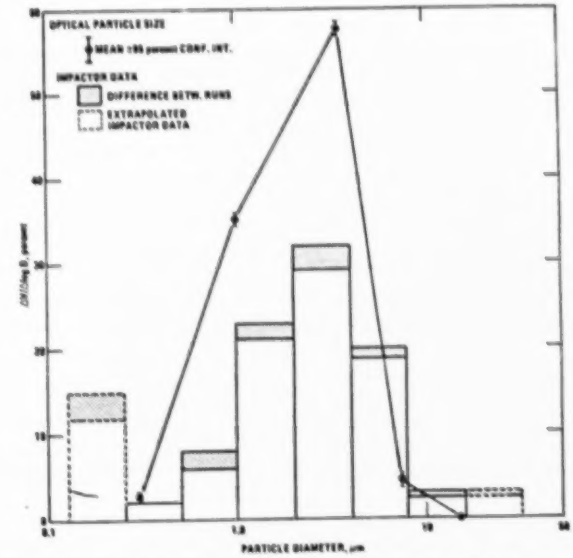

Figure 5. Optical and impactor particle size data for coal-fired power plant 2 with some ESP's turned off.

and impactor data agree that there is a peak around 1 μm. The second particle size peak indicated by the optical sizer around 15 μm is not defined by the impactor; however, the impactor does indicate a second peak between 16 and 32 μm if 32 μm is a valid upper particle sizing limit for the impactor data reduction for this source. Note that the upper sizing range of the optical sizer is reported to be 20 μm and exceeds slightly the upper sizing range of 16 μm defined by the impactor. The higher $\Delta V/\Delta \log D$ percentages indicated by the optical sizer are to be expected because the optical sizer assumes there are no particles outside of its sizing range, whereas the amount of particles outside the sizing range of the impactor is measured on its first stage and backup filter.

The data from the second coal-fired power plant are shown in Figures 4 and 5. In Figure 4, the data were obtained with all of the plant's ESP particulate emission control equipment operating. In Figure 5, the data were

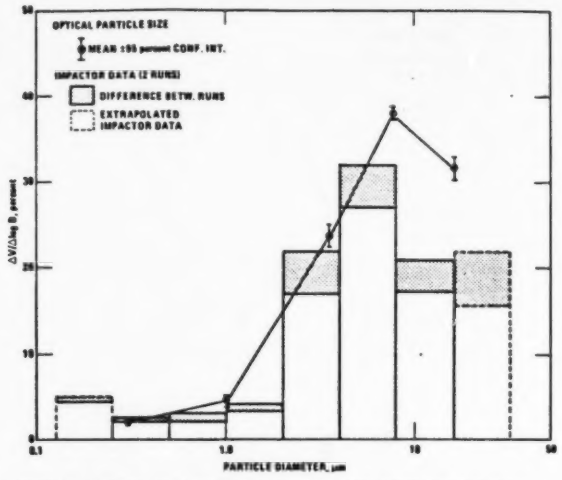

Figure 6. Optical and impactor particle size data for the SSSF.

obtained with some of the plant's ESP particulate emission control equipment not operating. With some of the ESP's turned off, the total particulate emissions increased by a factor of approximately 3.7.

In Figure 4, comparison of the two particle size curves shows that both methods define a particle size peak between 2 and 4 μm. As with the first coal-fired power plant, a large amount of fine particles below 0.25 μm is indicated by the impactor but not by the optical sizer. The existence of a secondary large-particle peak is not indicated by the optical sizer, and only a small large-particle fraction is suggested by the impactor.

In Figure 5, the impactor curve indicates that the only effect of turning off some ESP's was to reduce the fine-particle fraction below 0.25 μm. Since the optical sizer does not see this fine-particle fraction, very little effect can be expected on the optical size curve, and little was observed. No significant large-particle fraction was indicated by either method.

The data from the SSSF are shown in Figure 6. The SSSF data show a single particle size peak between 4 and 8 μm which was identified by both measurement methods. An insignificant fine-particle size fraction is indicated by both methods, and a relatively large, coarse-particle size fraction above 8 μm is indicated by both methods.

Table II shows impactor measurements of the particle concentrations of the sources and central tendency measurements of the particle size distributions by the impactor and optical sizer. The table shows that mean diameter measurements by the optical sizer were always greater than median diameter measurements by the impactor. This result would clearly be expected any time there is a large size fraction below 0.2 μm since the optical sizer does not account for these fine particles; however, the reason for the greater mean optical measurements for the two cases where the fine fraction is small is not as clear. These differences may be mostly inherent to the different measurement methods. The larger 36% difference occurs with the skewed SSSF distribution (Figure 6). The other test source with little fine particle fraction (Figure 5) shows a more log-normal distribution and smaller mean to median size measurement difference of 16%. This behavior between median and mean measurements of the central tendency of particle size distributions is expected (7).

It also should be noted that the impactor measurements may have been made too low by using a too-high-density adjustment for the impactor cut points. For example, if a density of 2.0 g/mL instead of 2.5 g/mL was used, the percent difference between the two tests without significant fine fractions would have been 8 and 25% instead of 16 and 36%, respectively.

Table II. Particle Concentration and Central Tendency Measurements of the Distributions

source no.	particle concentration,[a] mg/m³	impactor mass median diameter, μm	optical sizer volume mean diameter, μm	% difference
1	13–15	0.7[b]	5.0 ± 0.3[c]	151
2[d]	14–16	1.5	2.7 ± 0.1	57
2[e]	52–58	2.3	2.7 ± 0.0	16
3	57–72	5.9	8.5 ± 0.2	36

[a] At actual conditions. [b] Average of two runs. [c] Mean ± 95% confidence interval of 8–14 runs. [d] All ESP's operating. [e] Some ESP's not operating.

Conclusions and Recommendations

The optical sizer has been found capable of defining peaks between 0.2 and 20 μm in the particle size distribution of coal-fired power plant emissions. It does not measure particles that are smaller than 0.2 μm. This deficiency in the optical sizer measurements is serious if analysis of a large smaller than 0.2-μm size fraction is needed. The optical sizer may have some response to particles larger than 20 μm; however, this observation is not as clear as the observation of lack of response for the very fine particles, and it could have resulted from slight misalignments between the laser beam and the near-forward-scatter fiber optic probe during the tests. The first light-scatter angle is only 1.3° from the laser-beam axis.

Measurements of the central tendency of the particle size distributions showed the optical sizer volume mean diameter measurements always higher than the impactor mass median diameter measurements. This result is due primarily to the insensitivity of the optical sizer to the smaller than 0.2-μm particles and to inherent differences in the measurement methods when the distributions are skewed.

The effect of slight misalignment between the laser beam and light-scatter probes on large particles will be investigated. Additional sizing data should be obtained with the optical sizer on other types of sources and sources with known irregularly shaped particles. These data should also be compared with microscopic size measurements as well as impactor size measurements. The microscopic measurements are desirable because optical size measurements and aerodynamic impactor size measurements can be expected to deviate because of inherent differences in the measurement methods, particularly where irregularly shaped particles are measured. If these additional tests also show promise for the optical sizer, its lower sizing limit should be lowered. According to the instrument manufacturer, this lowering could be accomplished by using a shorter wavelength laser. A calibration technique should also be developed to provide the operator with a quick method of checking the calibration of the instrument in the field.

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